Improving Availability through Energy-Saving Optimization in LEO Satellite Networks

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Abstract. Recently, satellite networks are widely used for communication in areas lack of network infrastructures, and will act as the backbones in the next generation internet. Therefore, the availability of satellite networks is very important. In space, the energy is always limited for satellites, and highly efficient energy utilization would certainly improve the availability of satellite systems. In this paper, we consider the energy-saving optimization for the LEO satellite network instead of a single satellite. We modify and extend the multi-commodity flow model [3] to switch off satellite nodes and links as much as possible in LEO satellite networks. Taking advantage of the multi-coverage scheme and traffic distribution patents in satellite networks, we improve the heuristic algorithms in [3] to turn off the unnecessary satellites, up-down links and inter-satellite links respectively up to 59%, 61% and 72% under the constraints of link utilization and routing hops increase ratio, and the total energy saving ratio can be up to 65%. Finally, the availability of LEO satellite networks has been deeply developed.

Keywords: Reliability, energy-aware, low earth orbit (LEO) satellite network, snapshot routing algorithm, minimal cost multi-commodity flow model

1 Introduction

Since the inherent large range broadcast and rapid deployment property of satellites, satellite networks are widely applied in the emergent communication regions, oceans, desserts, and many other places lack of network infrastructures. Besides, satellite network will become an integral part of next generation internet in the future, so the availability of satellite networks is becoming more and more important. In space, satellites can only convert the solar power or nuclear power into electricity to support the control, maintaining and communication system as well as charging the battery. For the energy limitation of satellites, decreasing the energy consumption would certainly improve the availability of the satellite systems.

There are some researches focusing on the satellite energy-saving problems [7] [8], however, most of them aim at the energy and resource allocation of the single satellite, not the whole satellite network or satellite constellation. Compared to the durative solar-coverage of geostationary orbit (GEO) satellite, the low earth orbit (LEO) satellite would move into the shadow behind earth almost in every orbit cycle, and then only the battery can be available, which is the same condition as the wireless sensor networks [2]. For the satellite moving problem, we use the classic snapshot routing algorithm [9] to keep the network topology changing stably.

The idea of switching off devices as many as possible in terrestrial networks is provided in [3]. The network energy saving problem is concluded as an integer linear programming (ILP) problem under the constraints of connectivity and QoS, which is NP-hard and cannot be solved in polynomial time. The authors propose some heuristic algorithms to obtain the switching off ratio of nodes and links. For the LEO satellite network, the energy-saving can be achieved by distributing the traffic in proper routing paths and switching off the unnecessary satellite nodes and links. However, the tradeoff between routing hops, computational cost and energy-saving should be considered as well.

In this paper, we learn the idea of the link capacity constrained minimal cost multi-commodity flow model in [3]. By modifying and extending the model based on the special architecture of LEO satellite networks, we propose new heuristic algorithms, which can gain the switching off ratio of the satellite nodes, UDLs and ISLs up to 59%, 61% and 72% under the link capacity constraints, and the total energy saving ratio can be up to 65%.

The rest of the paper is organized as follows: the next section gives the brief overview of the researches on network energy-saving methods; the satellite network model is described in section 3; the energy-saving problem is formulated in section 4; the proposed heuristic algorithm is presented in section 5; section 6 gives the experiments design and simulation results; finally, the conclusions and future work are summarized in section 7.

2 Related work

The idea of saving the whole network energy by keeping the least necessary devices and links is firstly proposed in [4]. The authors use the standard minimal cost multi-commodity flow model (CMCF) to formalize the problem, but the complexity of the algorithms proposed increases rapidly with the devices adding in. Beside switching off nodes and links for energy-saving, many researchers take advantage of the low power mode and sleeping mode of network devices, such as [5][6], when there is no packets to send, the devices are set into the these modes to save energy.

However, the studies above are mainly focused on the terrestrial wired and wireless network, but for the special network topology and link characteristics in satellite network, direct deployment of current energy-saving methods cannot be efficient enough.

The energy allocation and admission control problem of single satellite is discussed in [7], and the authors use the dynamic programming methods to obtain the optimal transmission requests selection strategies for the maximum system profile. In [8], the authors send the multimedia broadcast flow in high bit rate burst instead of the continuous low bit rate mode, and turn off the RF elements to save energy in the spare time. However, these methods mainly discuss the energy allocation of the single satellite, not the whole satellite network or satellite constellation.

Since a large portion of satellite energy is consumed by wireless interface, such as up-down link (UDL) and inter-satellite link (ISL)[1], the method of switching off satellite nodes and links for energy-saving should be perspective in the global multi-coverage LEO satellite network in future.

3 Satellite network model

The satellite network model considered here is the iridium-like polar orbit constellation. As is shown in **Fig. 1**, the satellites constitute the Manhattan networks and are able to route data through ISLs. Every satellite has four ISLs: the up and down intra-orbit links are constant, and the left and right inter-orbit links are dynamic, which exist only between -60~60 degrees in latitude. For the predictable and periodic movements of satellites, every satellite network topology in each snapshot can be determined in advance. Meanwhile, we assume the traffic matrix in each snapshot is known in advance.

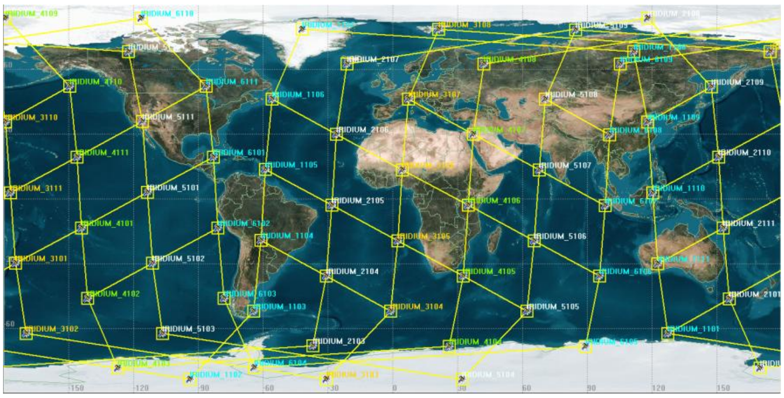

Fig. 1. ISLs topology in iridium system

To simplify the analysis, we assume that the satellite uses the single-beam transceivers, and each ground station is equipped with only one antenna, which connects to only one nearest satellite at one time. The ground station can see more than one satellite at anytime and anywhere, so we can lead the distributed traffic to the neighbor satellites under the UDL and ISL capacity constraints, and then close the redundant UDLs. Further, the ISLs with no traffic can be switched off, too.

The corresponding relationship between satellites and ground stations are one-to-multiple relationship. Each station is assigned with some channels of the big UDL. So switching off part of the up-down channel could only save the onboard processing cost, not the UDL energy of the satellite. Only when all the channels are closed, the UDL can be switched off.

However, switching off the satellite nodes and links would certainly increase the average routing paths and routing latency, leading to the computation cost and transmission times increase. But considering the communication components are always in effective work mode when power on, we simply assume that the device's energy consumption is independent of the transmission times.

3.1 Link capacity model

Since the network flow is used in our model, setting a practical link capacity could not indicate the link utilization of satellite network. We employ the initial maximal traffic values of all the UDLs and ISLs, represented by ${f_{max}}^{UDL}$ and ${f_{max}}^{ISL}$, as the base capacity factor and its β times as the upper-bound capacity of UDLs and ISLs, i.e.:

$$c^{UDL} = \beta * {f_{max}}^{UDL}$$
$$c^{ISL} = \beta * {f_{max}}^{ISL}$$

Obviously, current link capacity can meet the network traffic demands, but when part of the satellite nodes, UDLs and ISLs are switched off, the remaining UDLs and ISLs' capacities will be the limiting factors for traffic aggregation.

3.2 Network traffic model

The predict traffic distribution in 2005 [10] is shown in **Fig. 2**, and the original traffic in each cell is represented by f_{cell}. We use this data sheet for reference to generate our own traffic model. It is assumed that a ground station stays at the center of each cell. Let t^{sd} be the traffic factor between cell s and cell d. t^{sd} is in direct proportion to f_{cell}, and in inverse proportion to cell distance d(s, d), i.e.:

$$t^{sd} = \frac{f_s f_d * \gamma}{(d(s,d))^{\delta}} \quad \forall s, \ d \in V_{sat}$$

where γ=U[0,1] is the random number obeying the uniform distribution. Through adjusting distance coefficient δ, we can adjust the traffic distribution range between cells. d(s, d) represents the surface distance on earth between cell s and cell d, which is calculated as follow:

$$d(s,d) = \begin{cases} R * \theta_{sd} & s \neq d \\ \frac{R * \theta_{s(s+1)}}{2} & s = d \end{cases}$$

where the θ_{sd} represents the geocentric angle between cell s and cell d, and R is the radius of earth. When the traffic exists inside the cell, i.e. s=d, we use the distance between cell s and its right neighbor cell s+1 for calculation.

To adapt the generated traffic model to practical wideband mobile IP satellite network, we use the t^{sd} as the proportional coefficient for obtaining the simulated traffic values T^{sd} between cell s and d, i.e.:

$$T^{sd} = \frac{t^{sd}}{\sum_{s=1}^{N_{sat}} \sum_{d=1}^{N_{sat}} t^{sd}} * T_{total}$$

where T_{total} represents the total traffic values in the whole network (units: Mbps).

Intensity level and Corresponding Expected Traffic (2005)

Intensity level	1	2	3	4	5	6	7	8
Traffic (million minutes/year)	1.6	6.4	16	32	95	191	239	318

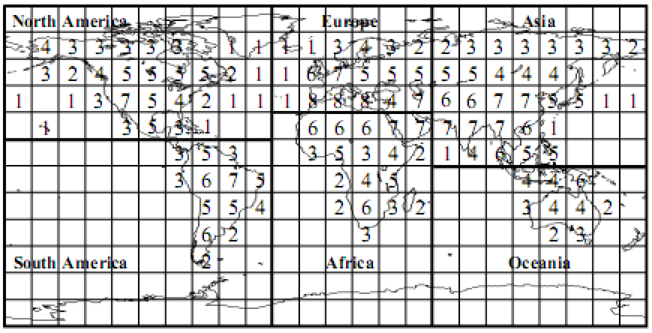

Fig. 2. Predict traffic distribution in 2005 (Millions of Minutes per Year) [10]

4 Problem formulation

More formally, we use the integer linear programming (ILP) method to define this energy-saving problem as same as [3], and also present the distinction between them, especially the up-down link broadcast communication characteristics between the satellites and ground stations.

The network infrastructure is represented as a di-graph G= (V, E), where the vertex set V represents the network nodes (including satellite nodes and ground station nodes), and the edge set E represents the UDLs and ISLs. The number of network nodes is N=|V|, and the $N_{ground}=|V_{ground}|$, $N_{sat}=|V_{sat}|$ represent the number of ground station nodes and satellite nodes respectively, and let the L=|E| be the number of UDLs and ISLs.

In the aspect of network traffic, we let T^{sd}, s, d= 1…N_{ground}, represent the total traffic between ground station nodes s and d; let $f_{ij}^{sd}\in[0,t^{sd}]$, i, j=1... N, s, d=1...N_{ground} be the traffic flowing through link (i, j) between node s and d. Let f_{ij}, i, j =1...N_{sat} be the total traffic flowing through the link (i, j), let $f_i^{UDL}\in[0,t^{sd}]$, i=1...N_{sat} be the total traffic flowing through the UDL of sat i, let f_i^{ISL} represent the sum of the ISL traffic flowing through satellite node i, i.e.:

$$f_i^{ISL} = \sum_{j=1}^{N_{sat}} f_{ij}^{ISL} + \sum_{j=1}^{N_{sat}} f_{ji}^{ISL}$$

Let $x_{ij}^{ISL}\in\{0,1\}$, i=1...N_{sat}, j=1...N_{sat} be binary variables that take the value of 1 if the ISL from sat i to sat j is present and power on. Similarly, let $y_i\in\{0,1\}$, i=1...N_{sat} be binary variables that take value of 1 if sat i is powered on. Let PL_{ij}^{ISL} be the power consumption of ISL between sat i and sat j, PL_i^{UDL} be the power consumption of UDL of sat i, and PN_i be the power consumption of sat i. PN_i contains the power consumption of OBP without UDLs and ISLs.

However, we should also consider about the bad impact for the routing hops and routing latency increase along with the satellites and links switching off. Let the $hop_{routing}$ denote the proportion of the number of all end-to-end routing hops in current static network routing to the one in initial state, and let hop_{flow} denotes the proportion of the number of all routing hops with flow passed by to the one in initial state. To keep the satellite network's latency performance in system level, we confine hop_{flow} should be smaller than $\eta \in [1, 2]$.

Given the definitions above, the problem can be formalized as follow:

Minimize:

$$P_{tot} = \sum_{i=1}^{N_{sat}} \sum_{j=1}^{N_{sat}} x_{ij}^{ISL} PL_{ij}^{ISL} + \sum_{i=1}^{N_{sat}} x_i^{UDL} PL_i^{UDL} + \sum_{i=1}^{N_{sat}} y_i PN_i \qquad (1)$$

Subject to:

$$\sum_{j=1}^{N} f_{ij}^{sd} - \sum_{j=1}^{N} f_{ji}^{sd} = \begin{cases} T^{sd}, & \forall s, d, i = s \\ -T^{sd}, & \forall s, d, i = d \\ 0, & \forall s, d, i \neq s, d \end{cases} \qquad (2)$$

$$f_i^{UDL} = \sum_{s=1}^{N} \sum_{d=1}^{N} \left(\sum_{j=1}^{N_{ground}} f_{ij}^{sd} + \sum_{j=1}^{N_{ground}} f_{ji}^{sd} \right) \leq \alpha c^{UDL},\ i = 1 \dots N_{sat} \qquad (3)$$

$$f_{ij}^{ISL} = \sum_{s=1}^{N} \sum_{d=1}^{N} f_{ij}^{sd} \leq \alpha c^{ISL}, i = 1 \dots N_{sat}, j = 1 \dots N_{sat} \qquad (4)$$

$$x_i^{UDL} + \sum_{j=1}^{N_{sat}} x_{ij}^{ISL} + \sum_{j=1}^{N_{sat}} x_{ji}^{ISL} \leq M y_i,\ i = 1 \dots N_{sat}, j = 1 \dots N_{sat} \qquad (5)$$

$$hop_{flow} \leq \eta \qquad (6)$$

Equation (1) minimizes the total energy consumption of the satellite network. Equation (2) states the classic flow conservation constraints, and the traffic can travel through the intermediate nodes in many paths without consumption until reaching the destination. Constraints (3) and (4) forces the link load to be smaller than maximum link utilization ratio $\alpha \in [0.4, 1]$, while constraint (5) states that a satellite node can be turned off only if UDL and all incoming and outgoing ISLs are actually turned off, taking $M \geq 2N_{sat}+1$. Constraint (6) forces the total hop counts increase should be under the maximum increase ratio η.

According to these equations above, this formulation falls into the class of link capacity constraint minimal cost multi-commodity flow problems as [3]. It is NP-hard, and cannot obtain the optimal solution in polynomial time. Therefore, a simple heuristic algorithm is provided to obtain the approximate optimal solutions.

5 Heuristic algorithms

We modify and consummate the heuristic algorithms proposed in [3], which is mainly used in terrestrial wired networks, and do not consider the special broadcast property of up-down links in satellite networks. In our algorithm, the full coverage of ground stations is checked at each node switching step, and the nodes and links are sorted every iteration to keep the selection greedy enough. The heuristic algorithm we proposed is shown as follows:

1. **Initial stage**: assume all the satellites, UDLs and ISLs are powered on, i.e. x_i^{UDL}=1, x_{ij}^{ISL}=1 (i=1…N_{sat}, j=1…N_{sat}). Then we use the dijkstra algorithm to calculate the satellite to satellite routing paths with the minimal hop counts, and distribute the traffic to the whole satellite network along these paths.
2. **Pretreatment stage**: switch off the UDLs and ISLs whose traffic equals zero and the satellite nodes whose UDL and ISLs both have been switched off.
3. **Satellite nodes switching off stage**:
   - Firstly, sort the satellite nodes in UDL traffic values f_i^{UDL} (UDLorder) or ISL traffic values f_i^{ISL} (ISLorder) ascending order. We do not sort the nodes by the incoming and outgoing degrees of satellite nodes because of its regular Manhattan network topology structure.
   - Secondly, iteratively switch off the satellite nodes and redistribute the traffic to the whole network. If the network flow can meet the flow conservation constraint (2), capacity constraints (3), (4), node switching off constraints (5) and the hop count increase constraint (6), the satellite node keeps off; or else, the satellite node should be switched on again, which gives the chance to the next satellite node.
4. **Links (UDLs and ISLs) switching off stage**: this stage is similar with the satellite nodes switching off stage. Because the satellites should cover all the terrestrial traffic demand, part of the UDLs could not be off even though the multi-coverage exists. Therefore, we optimize the UDL configurations before than the ISL configurations.
5. **Final check**: the algorithm checks whether there exists satellite nodes whose UDLs traffic and ISLs traffic equal zero, and it should be switched off, too.

6 Performance analysis

6.1 Experiment results

The energy-saving performance of proposed heuristic algorithms is evaluated in five different snapshots at different times, where the traffic is random with factor γ. The default values for all parameters are set as $\alpha = 0.5$, $\beta = 3$, $\delta = 1$, $\eta = 1.6$.

The energy-saving ratio is shown in **Fig. 3**. For the reasons of multi-coverage, 45% of the UDLs can be switched off in the pretreatment stage, and the traffic has been distributed throughout the whole network, so there are no satellite nodes that could be closed, and also only 2% ISLs could be closed. Compared to ISLorder heuristic algorithm, UDLorder performs better with the ratio of closed satellite node, UDLs and ISLs as 59%, 61% and 72%, respectively. Assuming that every satellite nodes, UDLs and ISLs have the same power consumption values, i.e. PL_i^{UDL}=PL_{ij}^{ISL}=100, PN_i=50, and the total energy saving can be up to 65%.

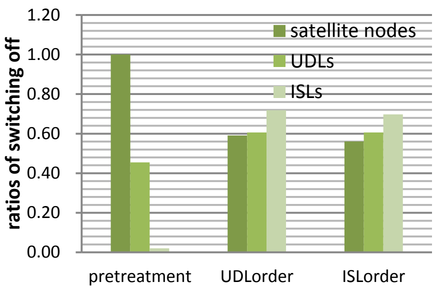

Fig. 3. Energy-saving ratio of satellite network

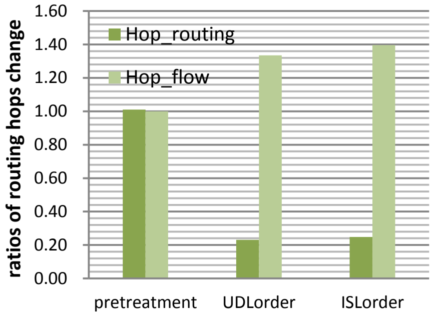

Fig. 4. Routing hops changes

As the satellite nodes and links switched off, the routing paths between each ground station pairs have been changed, along with the traffic distributions. The routing hops variations are shown in **Fig. 4**.

After pretreatment, the $hop_{routing}$ and hop_{flow} stay almost unchanged, because the satellite node, UDLs and ISLs are not switched off. After the UDLorder algorithm executes, satellite node switching off leads to the decrease of network nodes, and the routing path is simpler than before, so the $hop_{routing}$ decreases to 23% of the initial state. However, the switching off of satellite nodes and links obviously increases the average length of routing paths, so hop_{flow} increases rapidly up to 133% of the initial state, which means the average routing latencies increase largely.

The performance of ISLorder is also evaluated, and its increase ratios as $hop_{routing}$ and hop_{flow} are 25% and 140% of the initial state. Thus it can be seen that UDLorder is superior to ISLorder, partially because UDL is more important than ISL in satellite network.

6.2 Parameters impact

The impact of parameters to our energy-saving performance is studied as well. The link utilization ratio α and link capacity coefficient β mainly affect the switching off of satellite nodes and ISLs, as well as the UDLs traffic aggregation under multi-coverage, while distance coefficient δ is related to the traffic generation and distribution of the whole network.

Fig. 5(a) reports the switching off ratios for different δ values. As δ increase, the ratios increase slowly, however, UDLorder increases distinctly than ISLorder. And the curves of UDLorder-UDL and ISLorder-UDL are superposed together, since there are no changes in the terrestrial traffic aggregation while δ changes. **Fig. 5**(b) shows the variation of the ratios of nodes and links switching off versus α values. When α increase from 0.4 to 0.6, the energy-saving performance increase obviously, but when $\alpha > 0.6$, the energy-saving ratios become stable, because the link capacity is not the limiting factor anymore. In addition, the change of α values does not affect the terrestrial traffic aggregation, so the curves of UDLorder-UDL and ISLorder-UDL superposed together again. In **Fig. 5**(c), when η increase from 1 to 2, the energy-saving performance increase obviously, but when $\eta > 1.6$, the energy-saving ratios become stable, because almost all the redundant satellite nodes and links have been switched off, leaving not so much space for improvement.

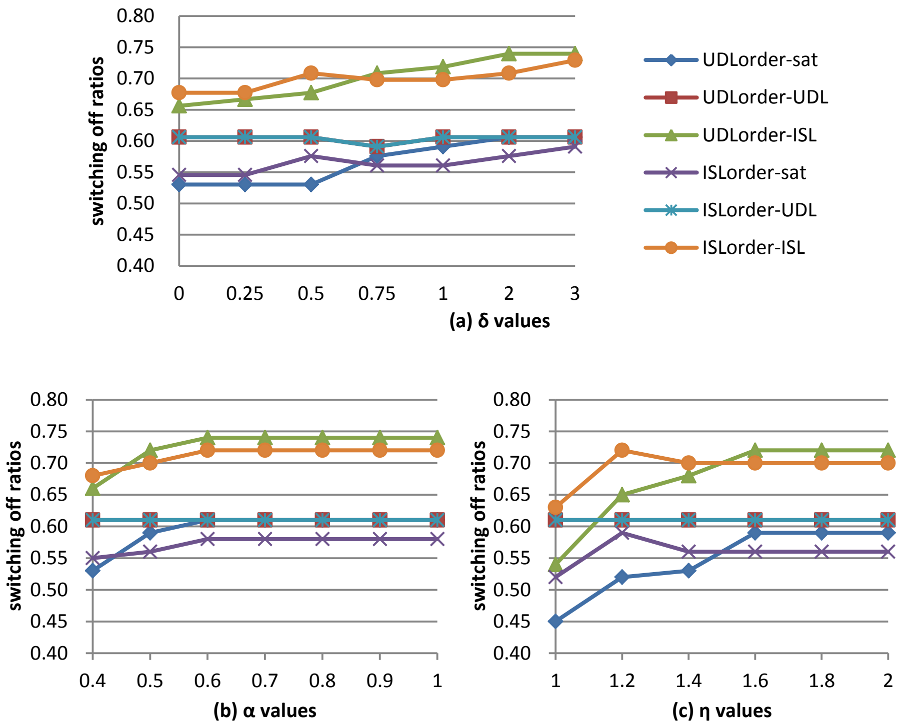

Fig. 5. Ratios of satellite nodes and links switched off versus δ, α and η

7 Conclusions and future work

In this paper, we discussed the availability improvement problem focused on energy-saving in satellite networks. Based on snapshot routing, we formulated this problem as a set of link capacity constrained minimal cost multi-commodity flow problems. We proposed simple heuristic algorithms to aggregate the distributed traffic in multiple satellites to a single satellite, and switch off the unnecessary satellite nodes, UDLs and ISLs, under the constraints of link utilization and routing hops increase. Results show that the total energy saving ratio can be up to 65% with the switching off ratios of satellite nodes, UDLs and ISLs being up to 59%, 61% and 72%.

As future work, we plan to consider the impact of variation of network traffic, which could be caused by satellite movements and the alternation of day and night. During the night, the traffic demand reduced largely, so more nodes and links could be switched off for energy-saving.

Acknowledge

The work described in this paper is partially supported by the grants of the National Basic Research Program of China (973 project) under Grant No.2009CB320503, 2012CB315906; the project of National Science Foundation of China under grant No.61070199, 61103189, 61103194, 61103182, 61202488, 61272482; the National High Technology Research and Development Program of China (863 Program) No.2011AA01A103, 2012AA01A506, 2013AA013505, the Research Fund for the Doctoral Program of Higher Education of China under Grant No.20114307110006, 20124307120032, the program for Changjiang Scholars and Innovative Research Team in University (No.IRT1012), Science and Technology Innovative Research Team in Higher Educational Institutions of Hunan Province ("network technology"); and Hunan Province Natural Science Foundation of China (11JJ7003).

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